

Small Unmanned Aerial Vehicle (S-UAV) Study for Civilian Applications

by

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Abstract

The design of a small unmanned aerial vehicle (S-UAV) is discussed here. Several markets where the S-UAV can be used were assessed to drive customer requirements, which the design was based on; missions for the military, law enforcement, environmental studies, police and news broadcasting, search and rescue and inspection were also based on the market assessment. A rotorcraft of 18 centimeters in diameter with two counter-rotating blades could satisfy customer needs and functional and performance requirements. The total weight is 1.4 kilograms and the thrust-weight ratio is 1.4. The S-UAV is capable of hovering, forward flight, vertical take-off and landing, and can be mounted with appropriate equipments according to the missions, e.g., camera for inspection. Since the S-UAV has to perform six different missions, the control system of the vehicle is categorized according to the missions. A detailed description of the control system structuring will be addressed in this thesis.

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Chapter 1

Introduction

Recently, the need for Unmanned Aerial Vehicles (UAVs) has increased in various fields from military to daily civilian application. Although military applications are more prevalent than civilian applications, the number of civilian users are growing because UAVs can play the same role as normal aircraft and do it more cost-effectively. Currently, several versions of UAVs are being flown, mostly in combat. Their sizes vary from one meter to more than ten meters. Massachusetts Institute of Technology - Lincoln Laboratory is developing a one foot wing span micro Unmanned Aerial Vehicle (μ -UAV) [5]. The comparison of these different UAV concepts is in Figure 1-1. As seen in the Figure 1-1, there exists a big difference between existing UAVs and the μ -UAV proposed by Lincoln Laboratory (LL).

The objective of this project was to design a Small Unmanned Aerial Vehicle (S-UAV) of a size smaller than existing UAVs but not so small as that of LL so it may play a role of a stepping stone between existing UAV's and μ -UAVs. The size of the μ -UAV makes this project very difficult. Searching for the right size of the components for μ -UAVs having excellent performance characteristics is one of the major problems that makes this project hard because the current state-of-the-art electric and mechanical components do not meet requirements. Making a μ -UAV depends not only on designing a configuration and solving engineering problems, but it also depends on other technologies such as Micro Electro-Mechanical Systems (MEMS), micro fabrication, etc., without which it is impossible to size down the

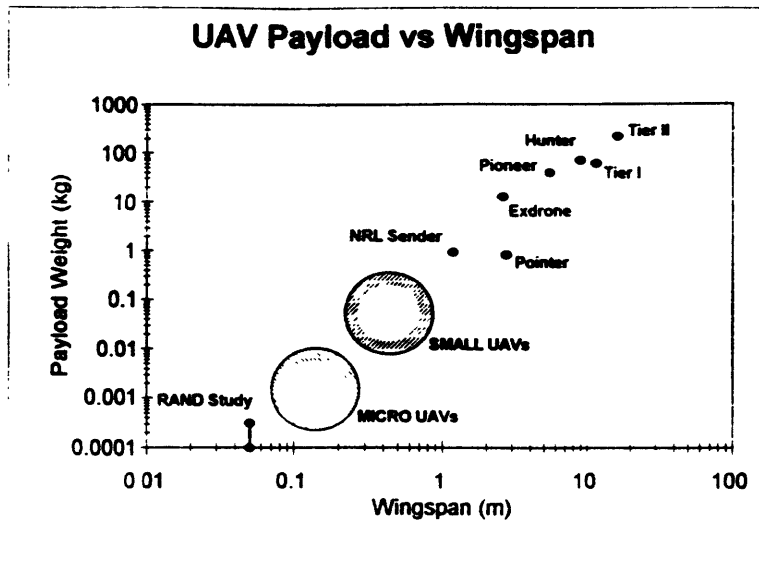


Figure 1-1: Existing and Proposed UAVs

vehicle.

The size of the S-UAV turned out to be an important factor that affects mission characteristics; therefore, we had to first decide which aspect of the UAV usage we are going to develop. For this project, we concentrated more on civilian applications while μ -UAVs are mostly for military application, and the design is based on today's technology. Therefore, although many inputs from LL were received during the project, only some of them were reflected in the design, which were applicable and necessary. We avoided adopting uncertain technologies that might be achievable in the future but are not available today. It turned out that the design can be significantly altered by those technologies in the near future. We tried to design the S-UAV as small as possible, so the factors that would increase size were considered very seriously. From the market assessment, it was found that each market requires different performance and functional requirements, so the team decided to design the payload attachable/detachable so the UAV can be used for various types of mission with an appropriate payload.

Chapter 2

Process

Figure 2-1 shows the plan for the project throughout the semester. Several visits to the Lincoln Laboratory were paid and design reviews took place almost every month until the end of the project.

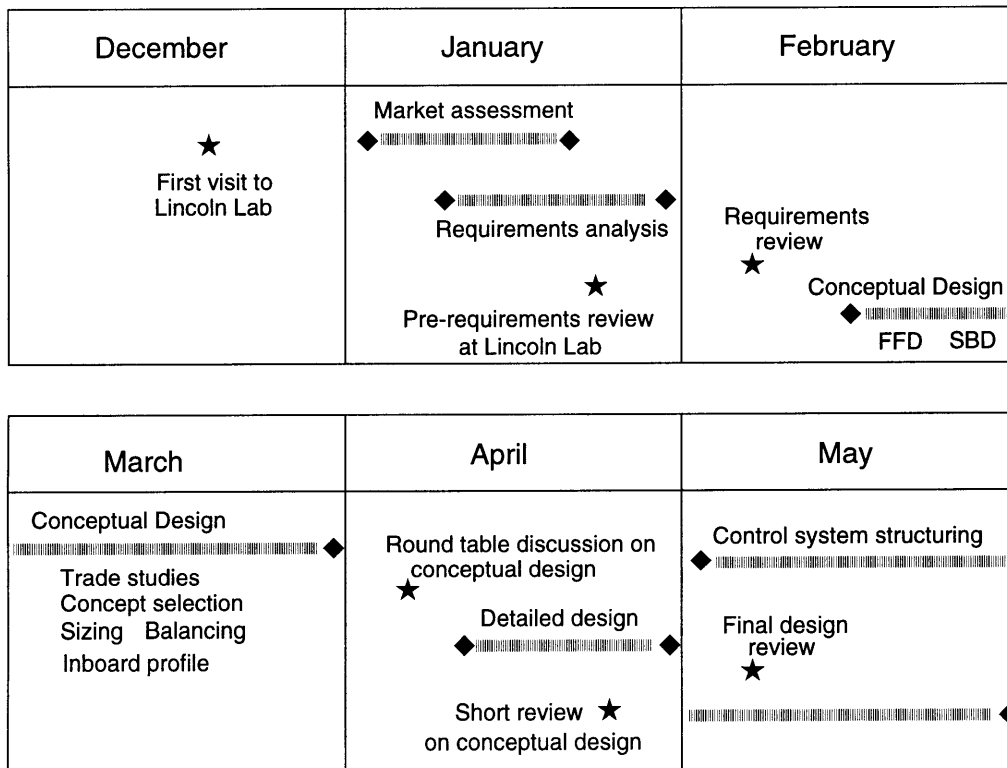


Figure 2-1: Project Process

The very first step before the design was to visit Lincoln Laboratory to hear their idea about μ -UAVs and the status of their research. Although the usage of the S-UAV may be different from that of μ -UAV, since their performance were similar and the ultimate goal of S-UAV was to make a closer step to μ -UAV, the visit to the LL was an important start. From the visit to the LL, we reconfirmed our design to be of small size and civilian-based.

Next step was to investigate various markets of S-UAV. Sampling a market for each possibility, team members went to potential users to get their thoughts about how S-UAVs could affect their work. By performing interviews, we wanted to figure out what the customer's needs and requirements would be. These interviews were done in January during MIT's Independent Activity Period. Getting all the inputs from the customers, we sorted the most feasible markets and prioritized the most essential requirements that the S-UAV has to meet. The customer requirements were converted into technical requirements by implementing a Quality Functional Deployment matrix. (see Chapter 4)

After analyzing the market assessment result and customer and technical requirements, we visited the LL a second time to see if the analysis was reasonable and got a positive feedback from them.

A preliminary Design Review followed and other people who were interested in the project; faculty advisors and people from Draper Laboratory also attended this meeting. Functional Flow Diagrams of the S-UAV with results from the previous research were presented. The input from the audience was a good basis for conceptual and detailed design.

During conceptual design, actual specifications for the S-UAV were developed, accompanied by Schematic Block Diagram and mission analysis. Configuration and trade studies were also done during this period; discussions with Professor Charlie Boppe and Professor Eugene Covert took place and a great amount of advice and suggestion were given to improve the design in a reasonable way. A round table discussion on the conceptual design was held before going into detailed design.

A more detailed and complex design was done after the conceptual design; the

suggestions and comments from the discussion with professors were reviewed and reflected on during the detailed design process. All the inputs from the previous design work were considered very thoroughly. Final design was reviewed in the middle of May. The comments from the audience were helpful to revise the team members' thesis.

Chapter 3

Market Assessment

Before designing the S-UAV, it is important for team members to know customer's requirements throughout possible markets so the S-UAV can be a useful tool for them. Team members chose six markets where S-UAV can be practically used, and contacted organizations in each of them to collect their thoughts and needs on having such a gadget in their field. This chapter describes the results of the interviews.

3.1 Military

Military is the market that the LL is developing the μ -UAV for. Although the team members agreed on concentrating on civilian market, the military mission was not ruled out. Among the military's requirements many similarities were found with other missions, e.g. mapping, surveying, and observation in that the S-UAV flies to a region of interest. It takes and sends image data to a ground station.

For the military mission, a high quality image sensor is very essential. Military mission is the one where the S-UAV can be used most uniquely with several features, e.g., covertness, safety (no need for a pilot to fly through dangerous zone), etc. Also, take-off and landing should be very convenient and possible in a very confined area, such as in the forest or near an enemy's fortress so that wherever the users reach the target region, they can send off the S-UAV to the place of interest.

3.2 Surveillance and Law Enforcement

The basic idea of this is to use S-UAVs as a flying security camera or a device to track a suspected person. This idea was mainly for the Police department. M.I.T. Campus Police Department was contacted; their major concern about using S-UAVs was the affordability issue. A police department like the M.I.T. Campus Police Department does not have enough budget to use this kind of equipment for their operation and actually such a small police department does not need to have it because most of the areas can be covered by a person. However, there may be those who can take advantage of having one. For the possible market of surveillance and law enforcement, an infrared camera is essential for a night mission, and hovering capability will be necessary in the case that the users want to take a closer look at a specific spot in detail.

3.3 Search and Rescue

The S-UAV can reach a place and take advantage of its mobile vantage point. Also, by using S-UAVs, the cost of sending a group of people can be greatly reduced. When it was a dangerous place where a disaster has occurred, it would be very useful to send a S-UAV to seek out people and see what has happened. Mission characteristics require long range, low cost but not small size, which contradicts our prediction.

3.4 Facility and Infrastructure Inspection

The benefits of the S-UAV for this mission are the cost-effectiveness and the safety. For example, for a bridge inspection, a company is currently spending 1500 dollars a day with problems causing traffic jams. There is danger because the boom that they are using requires people to actually go down below the bridge. By using an S-UAV with a decent quality camera all these problems can be resolved. This market was considered a major one throughout our design.

3.5 Environmental Studies

There are some environmental studies, which require taking data where it is hard to reach, such as above factories releasing lots of pollution or high in the atmosphere where moisture or temperature data should be taken for meteorological studies. Actually meteorology is using and is planning to use UAVs for their studies but since they have to load their equipments which are not necessarily small and actually most of which are too big for the S-UAV to carry, our project did not seem suitable for their uses. However, S-UAVs may be useful when the users need to sample data at many locations simultaneously. This can be another potential market only when S-UAVs are manufactured at low cost since the users have to use many of them. A low-cost-UAV that is convenient to operate should be a great attraction to those who are doing academic research.

3.6 Mapping, Surveying, and Observation

If these missions were to be done by a regular aircraft, it would be easily assumed that a pilot's role is not as important as in other missions that require good maneuverability. So, the main idea that determined this market to be one of ours, is that the same function can be done by S-UAVs. The S-UAV can use its freedom of vantage point for better observation. These are grouped together by similar purposes that the users want to have image data of the location of interest. S-UAV can fly to the point of interest, take a picture of it, send back the image data and return to the ground station. This idea itself was not pondered deeply during the project because the military mission has the same concept. Instead, the mission of news broadcasting was derived from this idea.

This market assessment shows that cost is more essential than the size or extremely good payload of the S-UAV. Except the military and the inspection company, most of the potential market recognized the S-UAV as an auxiliary equipment for their work although many of the customers showed great interest. The team concluded that the

S-UAV had to be very cost-efficient and easy/safe to use. A detail study follows in the next chapter.

Chapter 4

Customer Needs and Requirements

Based on the market assessment performed in January, team members developed the customer needs for six different markets including military applications. When we prioritized the customer needs, all the markets' needs were considered equally although it turned out that some of the markets showed more possibilities of using S-UAVs. This made the S-UAV have more flexibility and not be restricted to a certain mission; all the missions were considered and all the customer needs were prioritized in order of importance to all the missions. Requirements of the S-UAV were driven by the prioritization of the customer needs.

Once the customer needs were prioritized, we transferred them into technical requirements by using a Quality Function Deployment (QFD) matrix [4]. Through this process, a set of customer requirements were deployed and transferred into technical requirements. Figure 4-1 shows the table that prioritizes customer needs. The customer needs were all placed on the left column and each item was weighted differently according to its importance in the missions (highest 9, lowest 0). The weights of all the missions were added and the total score was used to determine relative importance of all the customer needs. This was then used for the QFD matrix. As a result, it was shown that the low cost and convenience of use are the most important requirement of the S-UAV as well as safety, which is reasonable in that for all the cus-

The UAV must be / must have	MARKET / MISSION							Total	Relative
	Police	Military	Inspect	News	S & R	Environ	Mapping	Importance	Importance
Easy to operate	9	9	9	9	9	9	9	63	10
Easy to support and transport	9	9	9	9	9	9	9	63	10
High endurance	9	9	9	9	9	9	9	63	10
Safe to operate	9	9	9	9	9	9	9	63	10
Low life-cycle cost	9	3	9	9	9	9	9	57	9
Operation beyond line-of-sight	9	9	1	9	9	3	9	49	8
All weather -capable	9	9	3	3	9	9	3	45	7
Short take-off & landing distances	9	3	9	9	9	3	3	45	7
Real-time data transmissions	9	1	9	9	9	3	1	41	7
Long range	9	9	0	3	9	3	9	42	7
Precise navigation/positioning capability	3	1	0	1	9	9	9	32	5
Hover-capable	9	1	9	9	1	1	1	31	5
Damage tolerant/robust	3	9	3	1	9	3	3	31	5
High quality images	3	3	9	9	3	0	3	30	5
Zoom-in/out capable	3	3	9	9	3	0	1	28	4
Infrared sensor capable	9	9	0	1	9	0	0	28	4
Handle large amounts of data	9	3	0	3	1	9	1	26	4
Low crash liability	9	1	3	9	1	1	1	25	4
Capable of different types of sensors	1	9	1	0	3	9	1	24	4
Capable of video transmission	9	1	3	9	1	0	0	23	4
Quiet and undetectable	9	9	0	3	0	0	0	21	3
Autonomous human ID & tracking	9	9	0	0	3	0	0	21	3
Very maneuverable	3	3	9	3	1	1	1	21	3
Non-intrusive to immediate environment	0	0	0	0	0	9	0	9	1

LEGEND

9	CRITICAL TO MISSION
3	IMPORTANT TO HAVE
1	USEFUL, BUT NOT IMPORTANT
0	NOT IMPORTANT AT ALL

Figure 4-1: Prioritization of Customer Needs

tomers, S-UAVs are not a critical tool but just a 'useful' tool to their work, regardless of missions. Figure 4-2 shows the QFD matrix used for deriving technical requirements. The customer needs with relative importance ratings are in the left column grouped into three categories, vehicle performance, interfaces and cost, and cooperational capabilities and system performance. Engineering characteristics/technical requirements to meet those customer needs are all listed at the top. Each of the engineering characteristics were weighed differently by each of the customer needs in the same manner as in the customer prioritization. All the numbers were added for each technical requirement to figure out the order of importance of them. One of the benefits of a QFD matrix is that we can see the conflicts between technical requirements. These conflicts are shown at the top of the engineering characteristics; the crossection of the conflicts are filled with a solid circle. These conflicts were taken into consideration during the conceptual design process to make an optimal design.

S-UAV

Small Unmanned Aerial Vehicle

Quality Function Deployment

		Engineering Characteristics		
Customer Attributes	Relative Importance	Engineering Characteristics	Relative Importance	
Vehicle Performance	High endurance	10	Satellite communications capability	10
	All weather-capable	7	RF modem communications	3
	Short take-off & landing distances	7	In-house data storage / retrieval system	9
	Long range	7	Flight autonomy	1
	Hover-capable	6	Collision avoidance system	3
	Damage tolerant/robust	6	Intelligent vision system	9
	Low Crash Liability	6	High bandwidth GNC system	9
	Quiet and undetectable	3	GPS capable	3
	Very maneuverable	3	Sonar navigation	3
	Non-intrusive to immediate environment	1	Visual navigation	3
Interfaces & Cost	Easy to operate	10	Altimetry	9
	Easy to support and transport	10	Off the shelf components	9
	Safe to operate	10	Few commands	9
	Low life-cycle cost	9	Graphic interfaces	9
Operational Capabilities & System Performance	Operation beyond line-of-sight	8	Virtual reality headset controllable	9
	Real-time data transmissions	7	Rechargeable power system	9
	Precise navigation/positioning capability	5	Few parts count	9
	High quality images	5	Shielded sharp blades and heat sources	9
	Zoom-in/out capable	4	Simple design	9
	Infrared sensor capable	4	Authoritative control response	9
	Handle large amounts of data	4	Small ground package	9
	Capable of different types of sensors	4	Laptop adaptable	9
	Capable of video transmission	4	Tethered battery/communications system	9
	Autonomous human ID & tracking	3	Large power supply	9

Total Score : 284
Relative Score : 5

Chapter 5

Conceptual Design and Trade Studies

Conceptual design and trade studies were performed for the purpose of both rough configuration and the optimal design among many variations. As was previously mentioned, a set of technical requirements were figured out, based on the result of the customer prioritization and QFD; they were sorted out in the order of importance. Conceptual design reflected the the important technical factors required to perform the missions. Detailed parametric studies were explained in a thesis of A.M.Leon. In this thesis, a brief discussion of the trade studies is addressed.

5.1 Mission Scenarios

After our second visit to LL, we narrowed down the missions to six different ones; these were the most feasible missions as determined by QFD, cost, inputs from the people, and technological aspects. We tried to cover all the possibilities of using S-UAV although there existed preferred missions which can be done only by S-UAVs. The six missions are illustrated in Figure 5-1.

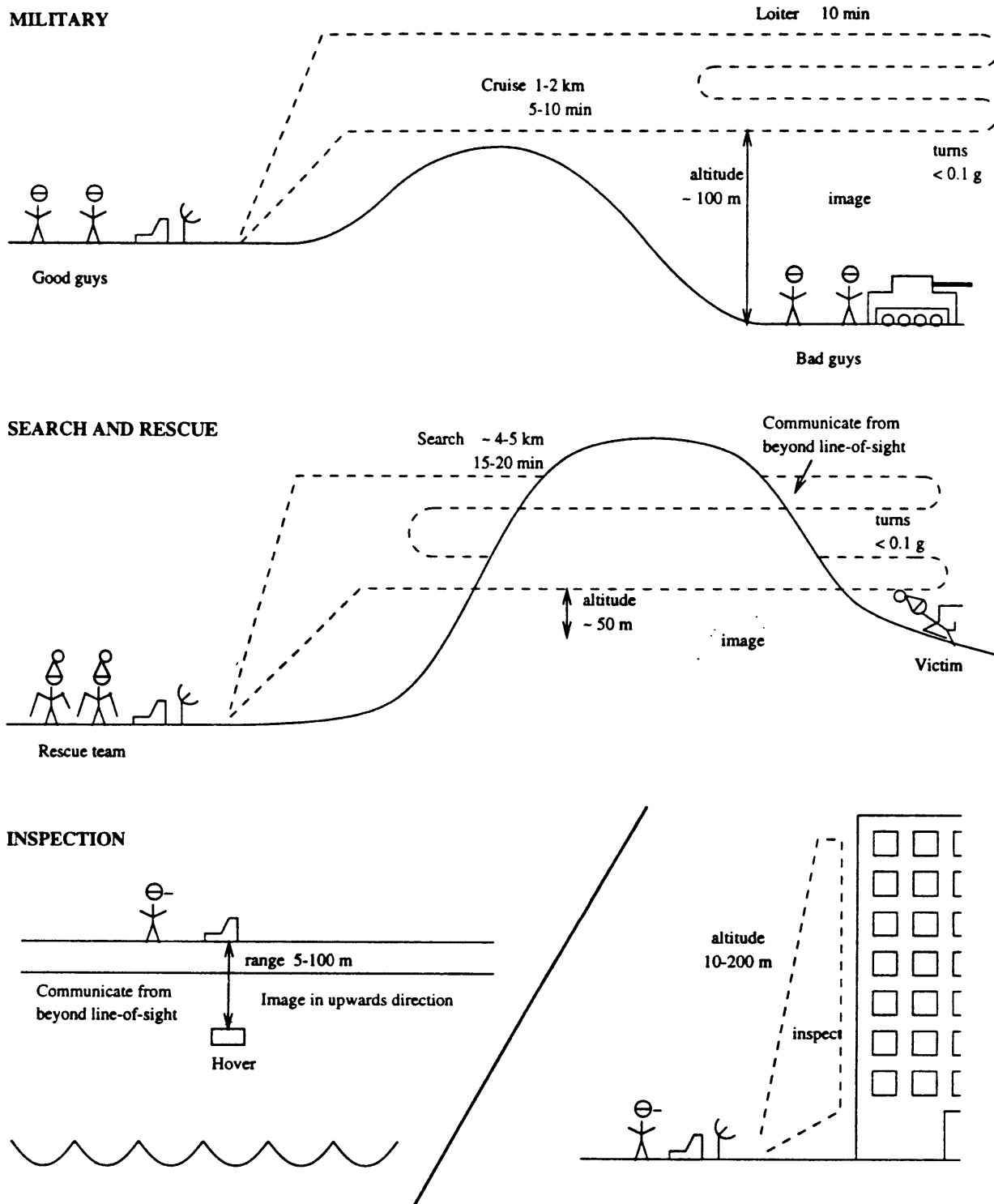
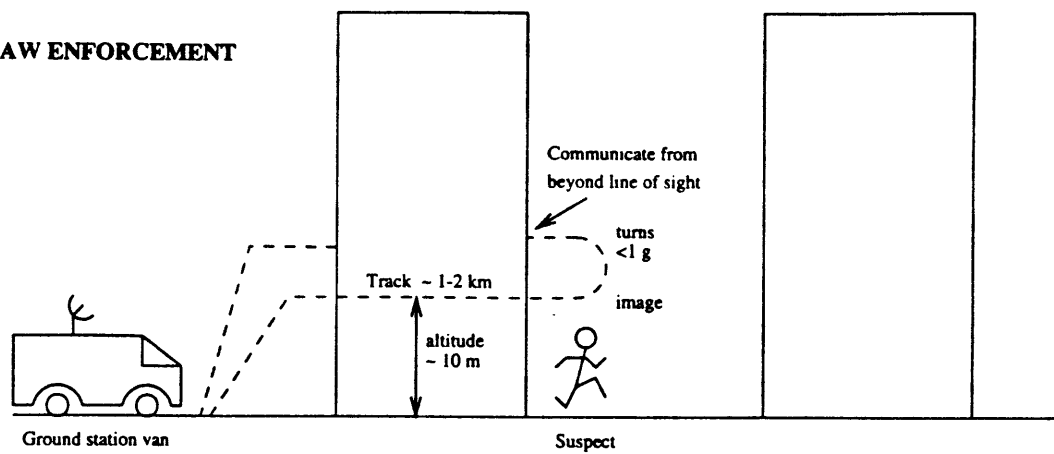
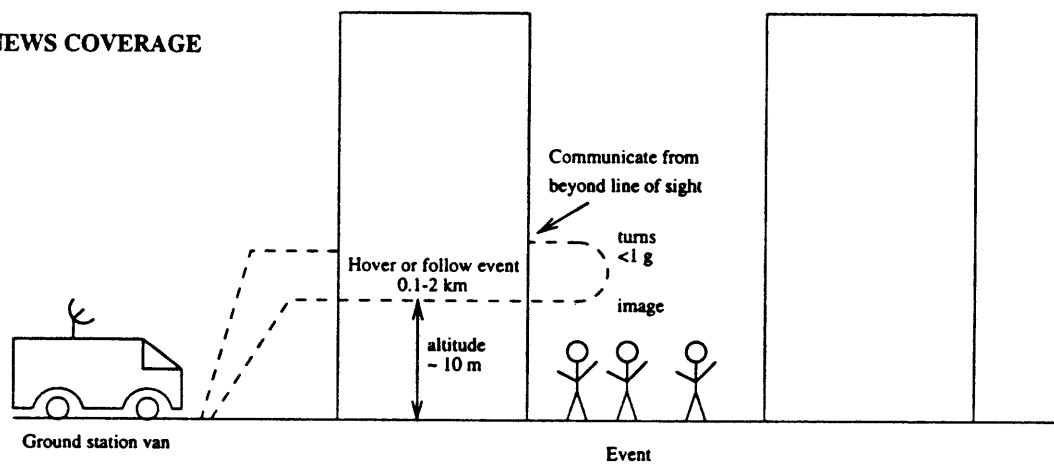


Figure 5-1: S-UAV Missions

LAW ENFORCEMENT



NEWS COVERAGE



ENVIRONMENTAL STUDIES

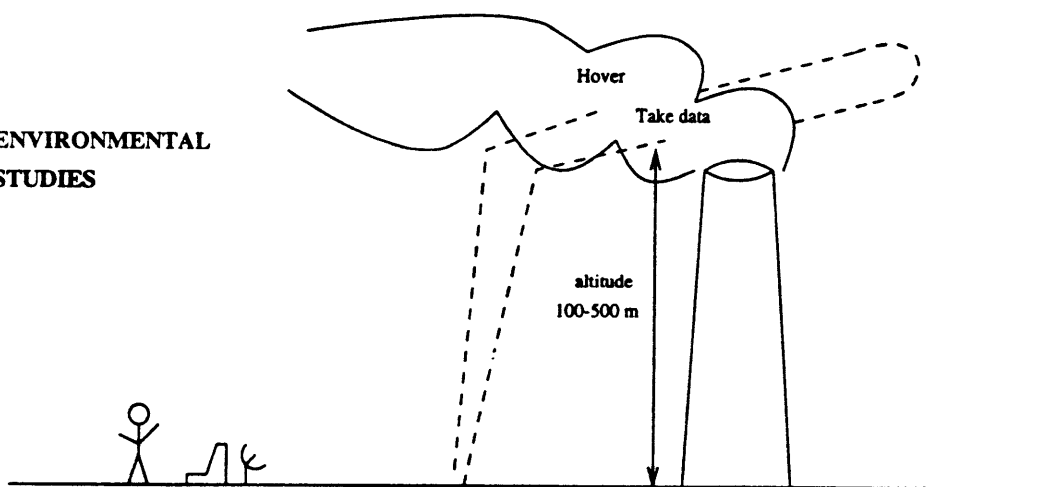


Figure 5-1: S-UAV Missions (cont.)

5.2 Functional Flow Diagram

A Functional Flow Diagram (FFD) is a pictorial presentation of the S-UAV operations in time sequence [4]. (see Figure 5-2) The FFD shows the general mission profile and not a particular mission, therefore, it is possible to find a different but better way to operate the S-UAV for different missions because there are many ways to do the mission and they can be all different. Some functions may be simplified or some functions can be performed more efficiently in different ways. This FFD provided a broad picture of total system operation and also helped the team avoid single-point design. Basically it consists of three parts: before take-off, flight, and landing. The first and the last part is least likely to change in any mission, but the second part, during the mission, it is possible that a different mission will have different ways to operate S-UAV more efficiently, depending on its functional and performance requirements. In the FFD, the functional flow starts at the top left. An ‘and’ symbol means all the blocks connected with it will be performed simultaneously, while the ‘or’ symbol means either of the functions in the blocks will be performed; anything in a box means system function or action. For example, during the flight, ‘acquire obstacle data-provide collision avoidance capability’ is connected by ‘and’, which means those two functions will be done all the time during the flight with other functions connected to the same ‘and.’

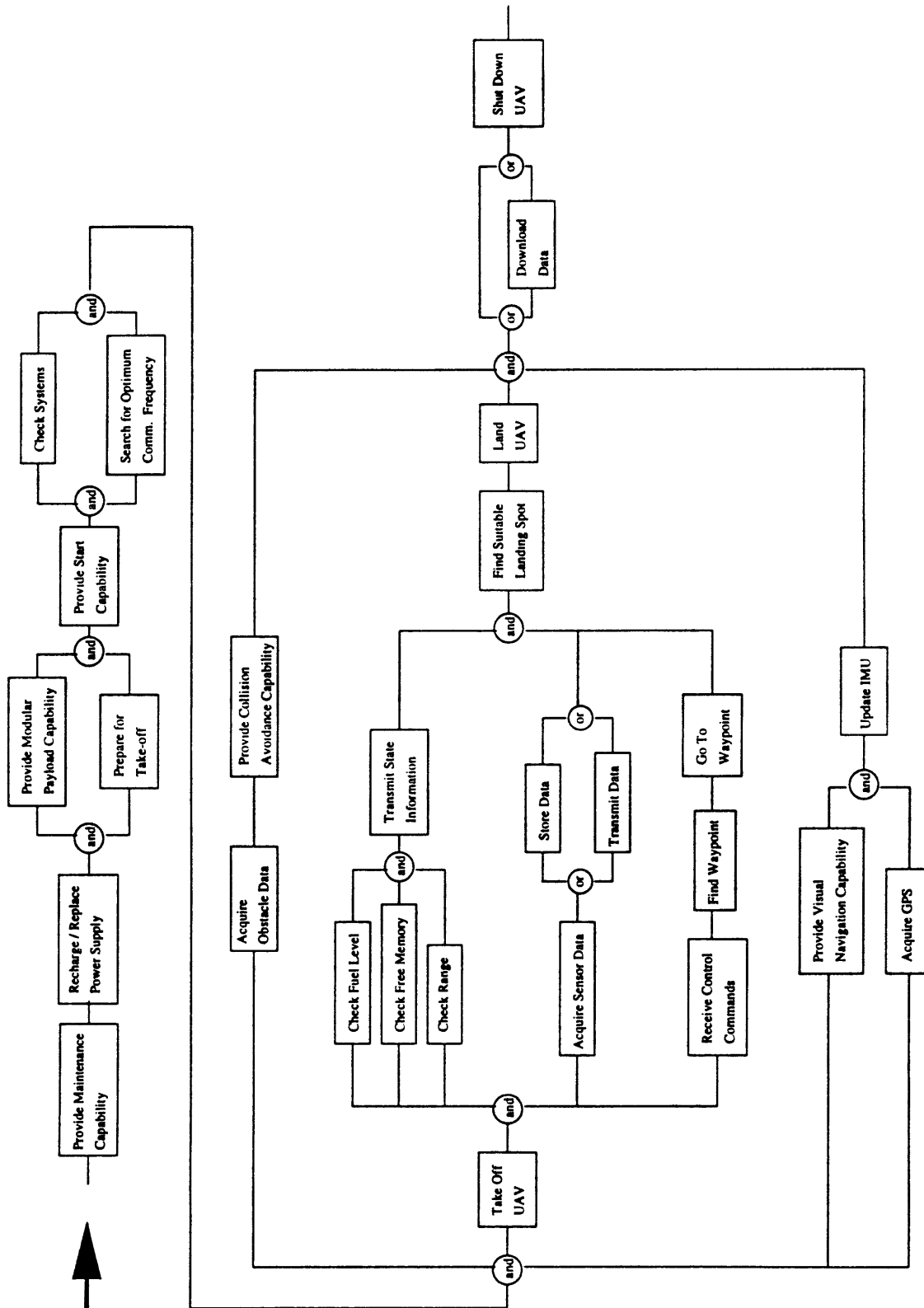


Figure 5-2: Functional Flow Diagram of S-UAV

5.3 Cost Estimate

To choose the right components and estimate the S-UAV's cost was a difficult part in the project because some of the equipments that we wanted to have in the S-UAV did not exist, so the cost is not easily determined. Especially, we could not find an Inertia Measurement Unit (IMU) that fits this S-UAV at reasonable cost. As is seen in the table 5.1 IMU cost is the biggest driving factor in the cost estimate.

Component	Cost
Voltage converters	\$100
Sonar rangers (2)	100
IMU	3,000
GPS	1,000
CPU (486) (2)	70
Radio transmitter	500
Antenna	50
Camera	250
Total	5,070

Table 5.1: Cost of Components

5.4 Trade Studies

Once the technical requirements were firmed, the next step was to determine the configuration of the S-UAV, which was optimal to meet all the requirements. There existed different design concepts, one of which was a rotorcraft with two counter-clock-wise rotating blades. A detail description of the trade studies with parametric analysis is in the thesis of A.M.Leon. In this thesis, I will briefly discuss how we came up with the ducted rotorcraft with gasoline engine.

The trade studies for outer configuration and the engine were done by comparing relative benefits of the two different options. First, figuring out the related technical requirements for each issue, we scored the options from one to five for each requirement; multiplying the relative importance by the score, and adding all the results we

Technical requirements	Score	Duct	No duct
Collision avoidance system	10	5	2
Lightweight	9	2	5
Modular payload	8	3	4
Stable aerodynamic configuration	7	4	3
Simple design	6	3	4
Small ground package	5	5	2
Few parts count	5	2	5
Efficient aero/propulsive design	5	5	5
Authoritative control response	5	3	5
Shielded sharp blades and heat sources	5	5	1
Water resistant	4	4	3
Hover-capable aero-propulsive configuration	4	5	5
Strong structure	3	5	3
Excellent manufacturability	2	2	5
Quiet propulsion system	1	4	2
Total		294	284

Table 5.2: Ducted Fan vs. Free Rotor

could get the total score for each option. As is seen in the table 5.2 and table 5.3, it turned out that ducted fan with electric engine was the optimal design for the S-UAV with the technical requirements driven from the QFD; however, currently existing batteries yield only 250 W·hr/kg, (see Leon's thesis for detail) which makes the design completely useless because for all the missions the endurance should be at least 15 minutes, which is not achievable with a battery. According to Leon, five minute endurance requires the energy density of 400 W·hr/kg. Although trade study showed some preference for electric engines, it was not a reasonable choice because it can not perform the mission at all. By knowing this and the score difference between the electric and gasoline engine, it was not seriously remarkable so we decided to use the gasoline engine.

Technical requirements	Score	Electric	Gas
High Endurance	10	1	5
Lightweight	9	2	5
Flight autonomy	9	4	3
Modular payload	8	4	4
Simple design	6	4	2
Tethered battery/communications system	6	5	1
Few parts count	5	4	1
Efficient aero/propulsive design	5	4	4
Authoritative control response	5	5	4
Shielded sharp blades and heat sources	5	4	4
Ground-based launcher	5	4	3
Large power supply	5	3	5
Water resistant	4	2	3
Off the shelf components	4	5	5
Hover-capable aero-propulsive configuration	4	5	3
Rechargeable power system	3	5	4
Non-flammable	3	5	3
Cheap power supply	3	5	3
Excellent manufacturability	2	5	2
Very low emissions/exhaust	1	5	1
Quiet propulsion system	1	5	1
Total		374	352

Table 5.3: Electric Engine vs. Gasoline Engine

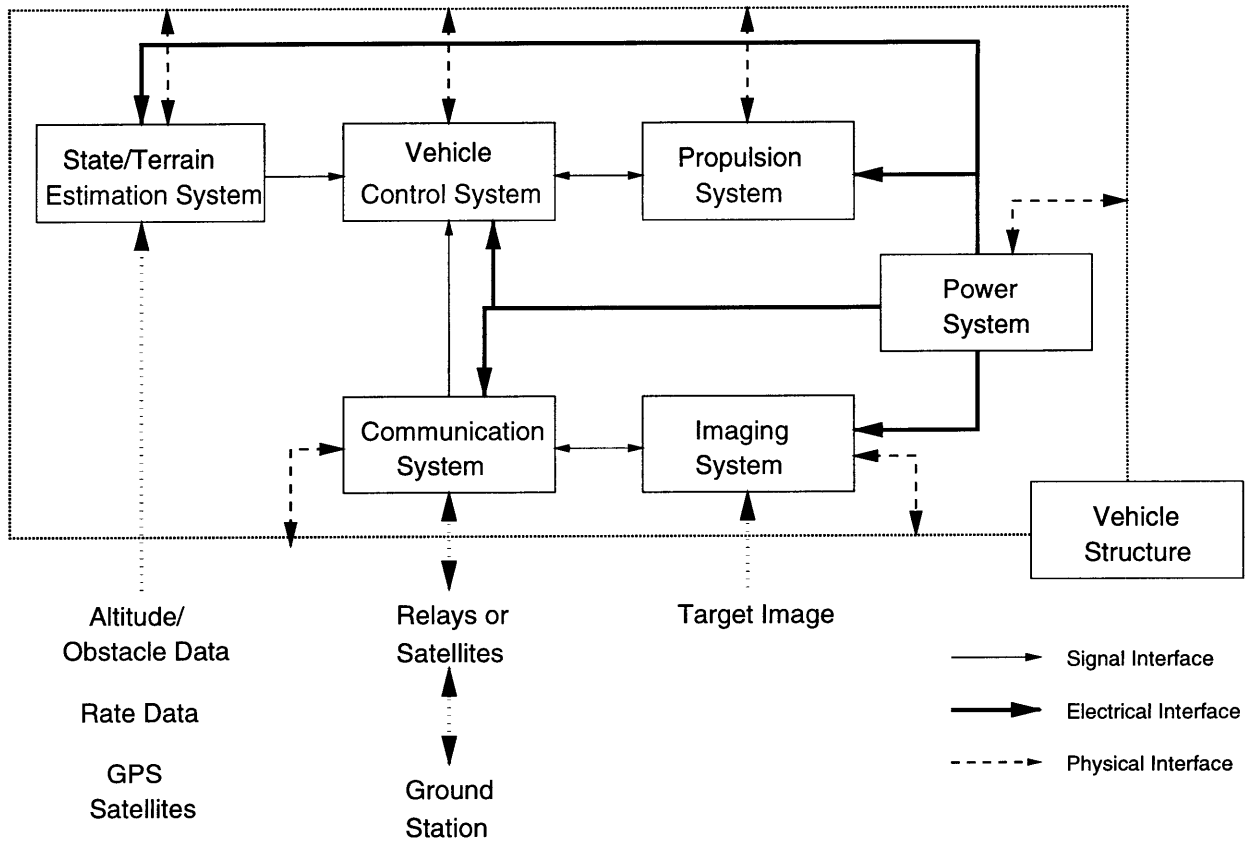


Figure 5-3: Schematic Block Diagram of S-UAV

5.5 Schematic Block Diagram

SBD shows a general overview of S-UAV system components and interfaces between them [4]. (see Figure 5-3) It consists of six different sub-systems; state/terrain estimation system, vehicle control system, propulsion system/communication system, imaging system and power system; all the subsystems are grouped by the vehicle structure. Different interfaces are denoted by different arrows. Each system must have subsystems of its own, however, as a top level design project, this thesis will not deal with a detailed explanation of each one. (D.Gordon [11] has more explanation on this in his thesis.) To briefly explain the SBD, all the systems are connected with the power system, which provides the electrical power to all the other subsystems.

COMPONENTS	WEIGHT (g)	Node	Front	Centre	Rear	Top	Bottom
Fuel	267	Components.	Voltage regulators	Body structure	Tail	Engine	Control surfaces
Voltage regulators	10		Sonar rangers (2)	Propeller	Radio transmitter	Fuel	Servo motors (actuators)
Engine	170		CPUs (486)	Gear box	Antenna	Fuel lines	Control surface sensors
Propeller	50		Camera	RPM meter		Fuel tank	
Gear box	30		Front structure	IMU		Battery	
RPM meter	5		GPS				
Fuel lines	10	Total Weight (g)	185	438	150	551	65
Fuel tank	30	X location (cm):	12	0	-12	-0.76	0
Body structure	293	Y location (cm):	0	0	0	0	0
Front structure	50	Z location (cm):	-2	-2.5	0.5	4.5	-8.5
Tail	80						
Control surfaces (fins)	40						
Servo motors (actuators)	20						
Control surface sensors	5						
Sonar rangers (2)	50						
IMU	60						
GPS	30						
CPUs (486)	30						
Radio transmitter	60						
Antenna	10						
Camera	15						
Battery	74						
Total weight (g)	1369						

Centre of Gravity:	X (cm):	8.00
	Y (cm):	8.80
	Z (cm):	8.39

Figure 5-4: Center of Gravity Positioning

The State/Terrain Estimation System gets the attitude data of the vehicle and the data for the obstacle and terrain; this subsystem consistently feeds the obstacle data to the Vehicle Control System so that the control system can maneuver the vehicle properly. The Vehicle Control System is for maneuvering the vehicle; inputs from the other subsystems except the imaging system are necessary to control the vehicle. The Propulsion System deals with the vehicle engine. The Communication System is responsible for sending data of the vehicle (data of attitude, position and obstacle ahead of it) or image and receiving commands from the ground station. The Imaging System can be replaced with other appropriate systems according to the mission. Here, the imaging system is responsible for taking image data of interest to the user. Detailed studies on the communication system and the imaging system can be found in the thesis of D.Gordon [11].

5.6 Positioning of the Center of Gravity

Previous research on a V-TOL vehicle showed the importance of the center of gravity of the vehicle. According to the paper presented by S. Ando [6], the stability of a ducted-fan V-TOL vehicle is highly dependent of the location of its center of gravity

and very sensitive; there is not much margin for stable center of gravity. The most important fact we adopted for the S-UAV is that the center of gravity should be located above the ducted fan. Figure 5-4 shows center of gravity location of the inboard profile (see Figure 5-5). All the structural components were used for the calculation and once the inboard profile was determined roughly, the components were grouped by five categories according to the position in the inboard profile. Since the location of the structural components is mostly fixed, the electronics were used to adjust the center of gravity. As is seen in the Figure 5-4, the propulsion system, which is the largest part of the total weight, was placed at the top of the vehicle. Other flexible components were placed appropriately to meet the requirement for the center of gravity. The center of gravity is located at $x:0.0$ $y:0.0$ and $z:0.39$, where the origin of the coordinate is at the center of the rotor. This calculation will ensure the stability of the S-UAV. Since the components are scattered and to be connected to one another, the internal wiring should be considered seriously in that the wire itself can increase the total weight. Detailed study was done by D.R.Gordon and there was found optimal placement, keeping the center of gravity still above the rotor and minimizing the total weight.

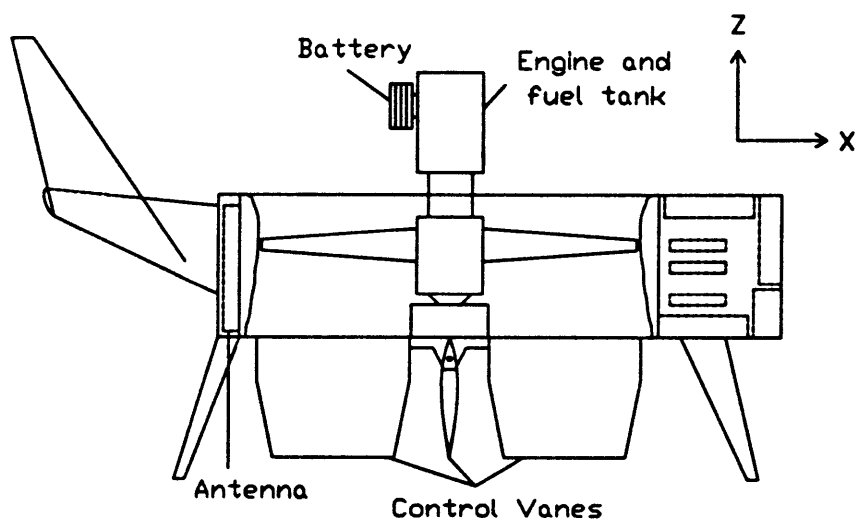
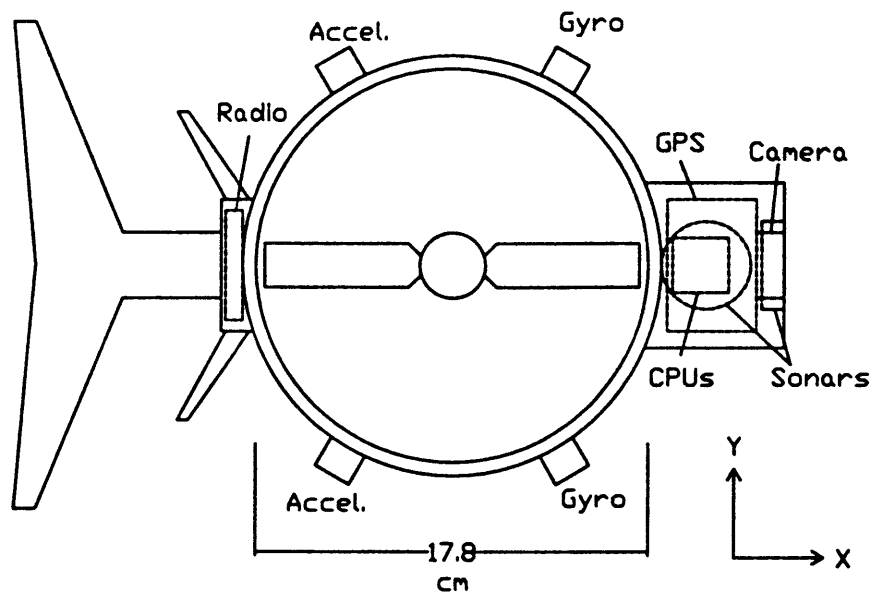


Figure 5-5: Inboard Profile of S-UAV

Chapter 6

Control System

6.1 Baseline Control System

The S-UAV will use a basic autopilot system; attitude-and-heading hold functions will work as a default to maintain the aircraft at the commanded attitude and heading. And a collision avoidance function will be implemented when necessary as it was found to be the most essential function of the S-UAV as explained in Section 4. Figure 6-1 shows the attitude control system block diagram for the S-UAV. Figure 6-2 shows the general block diagram of an aircraft navigation system. With the given data, the navigation system estimates the aircraft's position and velocity, with which the control system makes the aircraft fly as desired.

6.2 Control System Structuring

This S-UAV was designed to be used for six different missions as mentioned earlier. These missions were determined by seeing the possibility of UAV uses, and its feasibility in the practical world; specific requirements for each mission vary because different missions require different performance. Control modes are a means for adapting the performance for each mission. The control modes can be divided into three: The six missions may have six different control system, however, some of them can be grouped together by similarity of user's needs. The missions were categorized into

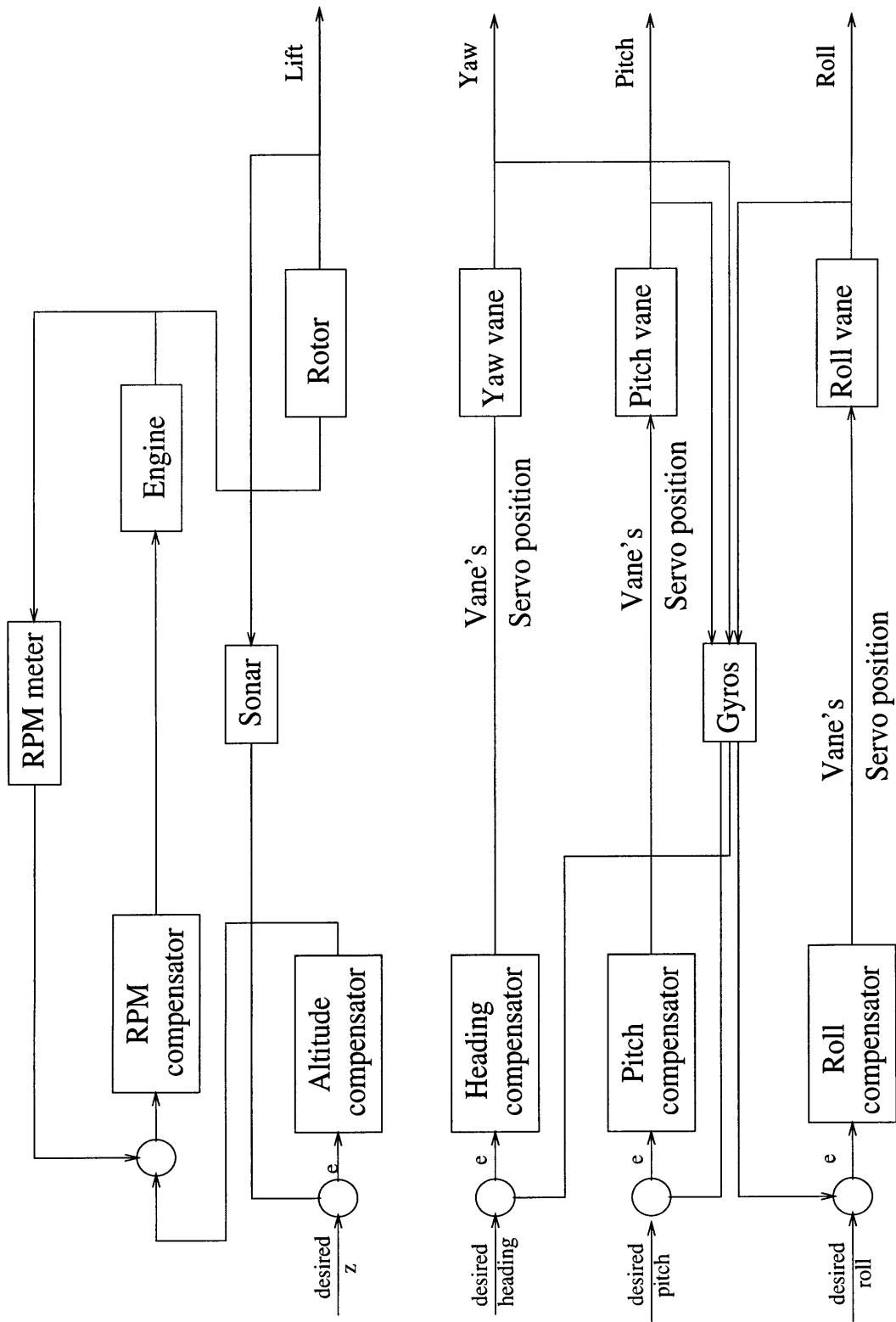


Figure 6-1: S-UAV Attitude Control System Block Diagram [6]

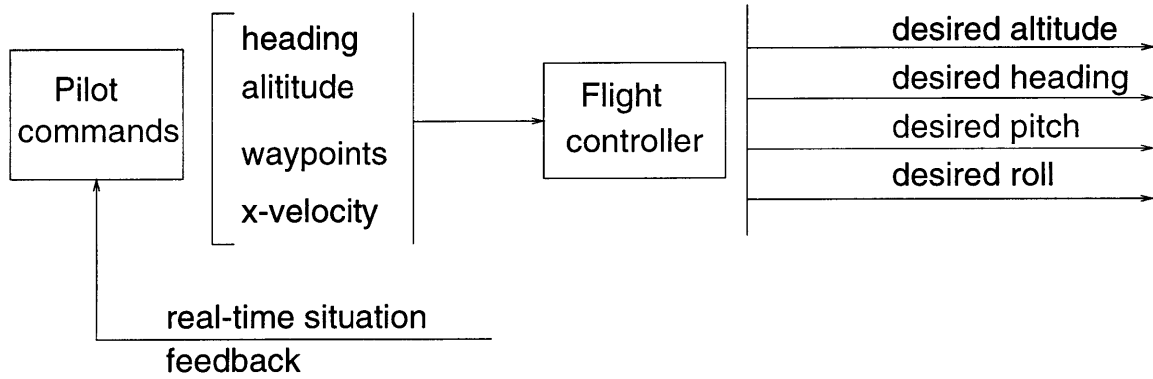


Figure 6-2: S-UAV Navigation System

three control modes; Table 6.1 shows the grouping of the missions, each group will have the same control system and will use the same command from the user.

Control modes	Missions
Inspection mode	facility/infrastructure inspection, environmental study
City mode	police, news
Terrain mode	search/rescue

Table 6.1: Control Mode Category

6.2.1 Inspection mode

Inspection mode deals with the inspection mission and environmental study mission. For these missions, it can be reasonably assumed that the vehicle will fly near the user and the user knows the object to be inspected very well; the vehicle will be always in the line of sight so the user can adjust its location by actually seeing it, therefore a highly accurate guidance system may not be necessary. This will reduce the total cost and make the system simple. The cost for an accurate guidance system with GPS and a high quality IMU is the major portion of the total. (see section 5.3)

In the general control system for an aircraft, the state vector of the vehicle can be estimated by sensors and the measured data will be used to close the feedback loop. For the inspection mode, some of the sensors may not be needed, instead, the user will be a feedback and close the system by taking advantage of proximity to the vehicle and the camera image sent from the vehicle. Since the behavior of the vehicle in the inspection mode is predictable and the user has the most maneuverability, and the vehicle is assumed to fly very slowly, the collision avoidance system in this case will simply maintain a certain distance to the object all the time.

6.2.2 City mode

City mode is for the law enforcement and news broadcasting mission. These missions are grouped together by the fact that both missions are performed in a city, where many people and buildings are obstacles to the vehicle. This S-UAV mode must have more reliable, accurate navigation system and is probably more complicated than the others. Once a destination is determined, waypoint navigation should work with a waypoint manager in the ground station. Digital maps will be necessary for this function. The waypoint manager will figure out the most efficient way to get to the target point in terms of proper waypoints. Street names and notable objects can be used as waypoints.

For the feasibility of maneuvering along the street or the road, and the limit of the width of the roads that can be used as the path, a calculation of the turning radius was done and explained in section 7.1. For an accurate navigation inside a city, Differential GPS (DGPS) is suggested to be used, because the vehicle has to keep the path by the error of half the width of the road. Users may use a moving map display to locate the vehicle.

Another important thing in the city mode is the safety issue due to the nature of the environment where the vehicle performs its mission. Cities are densely packed with people and buildings. Although the S-UAV was designed to minimize harm to people in case that any collision takes place, there needs to be a more reliable tool to ensure the safety. (For a detailed description, see the thesis of A.M.Leon [12])

As a means of that, a collision avoidance system is necessary as well as a maximum speed regulation system. It will help the vehicle maintaining the most safe speed. A description for the collision avoidance system will follow in section 7.2

6.2.3 Terrain mode

Terrain mode is basically the same as the way normal Radio-Controlled aircraft fly. Heading and altitude commands will be sent to the vehicle; up to a certain point, waypoint navigation can be used because the mission does not require any specific functions to be done until it reaches the destination. Search and rescue missions in an open terrain and military missions will use this mode. As was the case in the city mode, a moving map display will be used to locate the vehicle in the field. For the terrain mode, it is assumed that the mission will be done in an open terrain field, which is different from the city mode, where lots of obstacles can be found, therefore, there will not be a need for a DGPS.

Chapter 7

Collision Avoidance System

This chapter discusses the feasibility of the S-UAV collision avoidance system. Since the most important feature that the S-UAV has to have is the collision avoidance system, it is important to verify the S-UAV can actually fulfill the required function.

There can be many ways to avoid collisions , however, since we are using just two sonar sensors, one at the head of the vehicle and one at the bottom of the vehicle, the information on the obstacle which is located near the vehicle may not be sufficient to apply a simple and easy algorithm. To support a detailed algorithm for collision avoidance, simulations were performed to understand relevant dynamics and to verify the feasibility of implementing the function with the designed features. The following symbols will be used in this chapter.

A : area of fan

D : diameter of the rotor

g : gravitational acceleration

m : vehicle mass

T : thrust

t : time

U_d : horizontal speed

H : drag force

V : axial air velocity through the duct

ρ : density of air

θ : pitch angle of vehicle, positive nose down

ϕ : bank angle

ψ : yaw angle

d_{th} : threshold distance between vehicle and obstacle

R : turning radius

7.1 Dynamics

To make the collision avoidance function feasible, it is necessary to understand the dynamics of the vehicle since it is crucial that the vehicle makes a right turn at a spot where the vehicle has enough room to make a safe turn without colliding with anything around it.

Before the actual simulation, it was necessary to figure out the reasonable forward speed of the S-UAV. The forward speed determines S-UAV turning radius and also the distance from the obstacle where the collision avoidance function has to start. Since the drag force was proportional to the forward speed, there is a limit that the vehicle can reach at most. According to Ando [6],

$$T = \rho A V^2$$

$$H = \frac{\frac{1}{2} T^{3/2}}{\sqrt{\rho A}}$$

$$V = \sqrt{\frac{T}{\rho A}}$$

$$F_x = T_x - H = m a_x$$

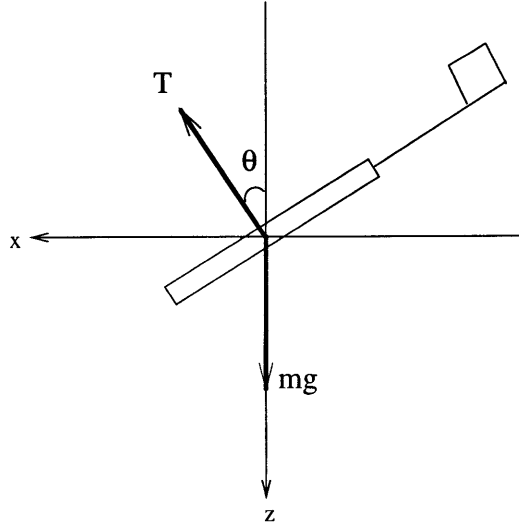


Figure 7-1: Coordinate System

$$a_x = \frac{1}{m} (T_x - U_d \sqrt{\frac{T_x \rho A}{\sin \theta}})$$

for a level flight (see Figure 7-1),

$$T \cos \theta = mg$$

$$T = \frac{mg}{\cos \theta} = \frac{T_x}{\sin \theta}$$

$$T_x = mg \arctan \theta$$

$$\theta = \arctan\left(\frac{T_x}{mg}\right)$$

Since $T = \frac{T_x}{\sin \theta}$, the x-direction acceleration can be expressed only in terms of T_x when theta is assumed to be the maximum theta for a level flight. By integrating the acceleration with different T_x 's, we can get U_d 's. The forward speed is a function of theta and the thrust and a level flight gives one condition that the weight of the vehicle should be equal to the vertical force created by the thrust; this condition determines the theta. Therefore, T_x is the only parameter for U_d 's. Figure 7-2 shows

that the maximum forward speed increases almost linearly with x-direction thrust (thrust-to-weight ratio is 1.4.)

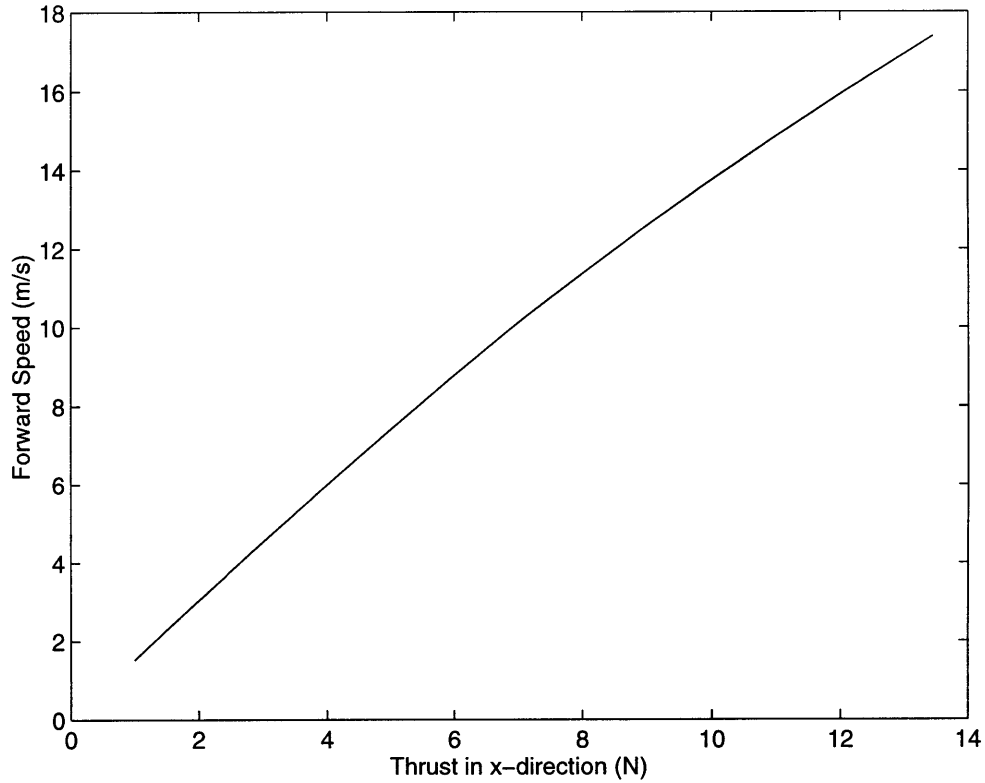


Figure 7-2: Maximum Forward Speed vs. Thrust

For conventional winged aircraft, a banked coordinated turn is used when making a turn (see Figure 7-3 (a).) The turning radius is determined by bank angle ϕ and forward flight speed U_d ($R = \frac{U_d^2}{g \tan \phi}$.) Since T_x determines U_d and ϕ in level flight, the turning radius can be also expressed in terms of T_x . Here, it is assumed that S-UAV is using the coordinated turn. However, in the rotorcraft like S-UAV, there may be another way to make a turn. This would involve decreasing the velocity ultimately to zero and then rotating the vehicle itself (see Figure 7-3 (b).)

To determine where the collision avoidance function starts relative to obstacle, critical distance was calculated. The critical distance is the distance between the

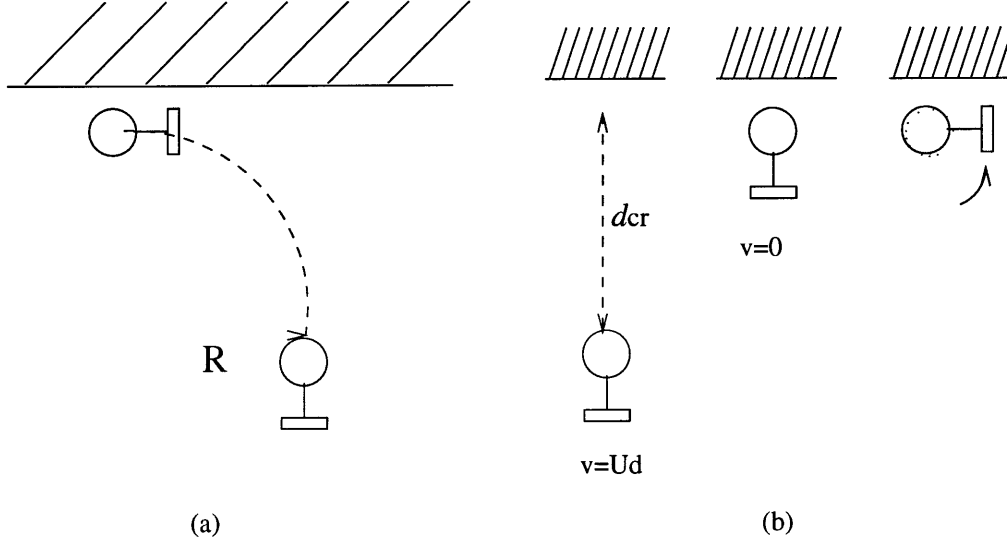


Figure 7-3: Banked Turn and Stop/Rotate

point where the thrust starts being applied in opposite direction to the vehicle's flight direction and the point where the flight speed decreases to zero (see Figure 7-3 (b).) A comparison was made between the turning radius and the critical distance. Figure 7-4 shows the critical distance vs. initial flight speed when the thrust applied in x-direction is 3 N and 13 N. (For level flight, maximum available thrust in x-direction is $1.4(1.4 * 9.81) \sin \theta = 13.4 \text{ N}$, when $\theta = \arccos(\frac{1.4*9.81}{1.4(1.4*9.81)}) = 44^\circ$.) Although the author used the conventional banked turn for the simulation, the stop/rotate-turn might be more feasible because the vehicle does not turn making a circle inside which there has to be no obstacle for a safe turn. (When S-UAVs fly in a city with the waypoint navigation active, it will be safer just to stop and rotate because the cross sections where the vehicle is likely to make a turn may not have much space around the vehicle.) The turning radius of the coordinated turn is larger than the critical distance when the vehicle has the same forward flight speed. Especially, when the forward speed is high, the turning radius becomes so large that it better not be applied in the collision avoidance function. However, typical mission speed requirement is between 15 and 25 km/h , which is between 4 and 7 m/s , therefore a reasonable turning radius can be obtained by choosing a proper T_x .

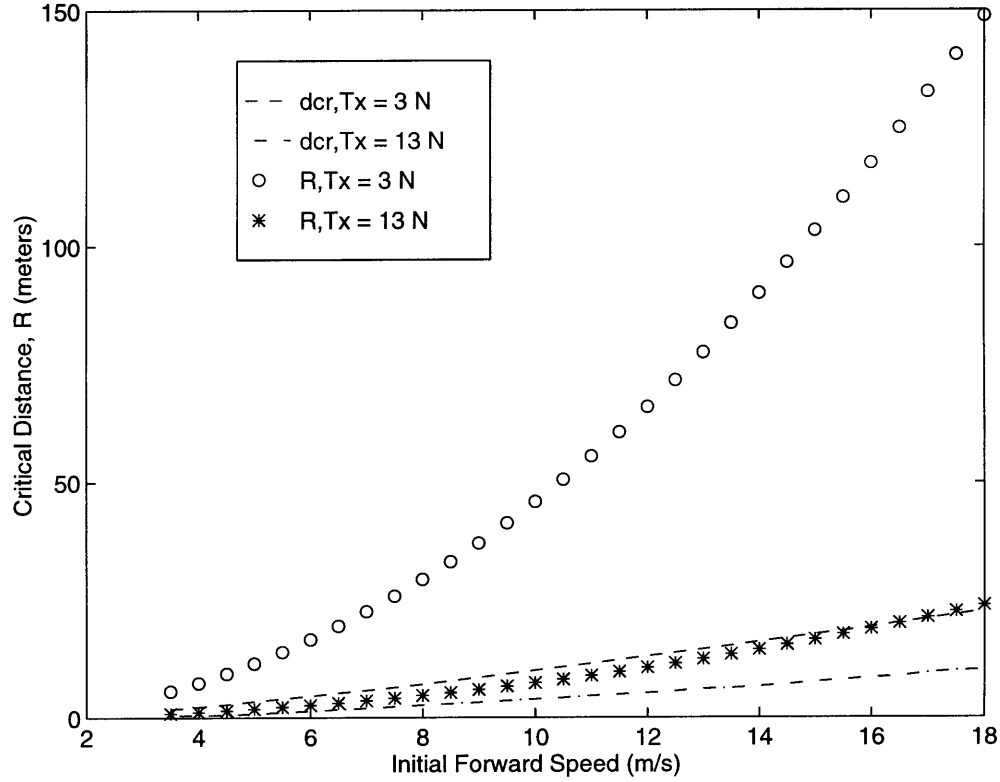


Figure 7-4: Critical Distance and Turning Radius vs. Initial Forward Speed

7.2 Algorithm

The S-UAV uses two sonar sensors for the collision avoidance system; one is located at the bottom of the vehicle, and the other is on the front of the vehicle. (see Figure 5-5) Each sensor is responsible for detecting the distance to the ground and object in front of the vehicle respectively. While collision to the ground can be avoided simply by climbing up and maintaining a safe distance between the vehicle and the ground, the collision avoidance with objects that hinder the vehicle from flying directly to the target place is a more critical problem to be solved. The first step in avoiding collisions is to detect any dangerous object in the surrounding area. Then a precise way to maneuver to avoid collision with the object should be determined. Since the sonar sensor is fixed in front of the vehicle, the vehicle only can get the information on

the object located in the direction of the vehicle heading. This means that it cannot detect anything around the vehicle unless it blocks the vehicle. The problem occurs when searching for a right way to avoid the hindrance. With one sonar sensor at the front of the vehicle, it is impossible to figure out which direction is away from the object at the same time of detecting the object. Therefore, in order to find a right way to avoid collision, it is necessary for the vehicle to turn around to get information on the surroundings.

Once the collision avoidance function starts (when the vehicle starts turning), it will continue until there is no obstacle ahead of the vehicle and the vehicle flies almost at the commanded heading angle.

The baseline of the algorithm is to find where there is no obstacle and fly toward that point. If that direction is secure, it uses the feedback heading command again to redeem the original heading angle. Figure 7-5 shows a closed loop feedback system with a heading command as a reference input. The input switches between the desired heading angle rate and output from the collision avoidance function. By approximating $\phi \approx K\dot{\psi}$, each output of $\dot{\psi}$ will determine the input to the point-mass model by using the following algorithm:

Inputs: $d, \psi_{command}, \psi_{real}$

Outputs: $\dot{\psi}_{new}$

Step 1 If $d \leq d_{th}$, do *Steps 2-3* until $\psi_{command} - \psi_{real} < TOL$ and $d = \infty$.

Step 2 if $d = \infty$, set $\dot{\psi}_{new} = G(\psi_{command} - \psi_{real})$

else

Step 3 set $\dot{\psi}_{new} = \frac{44\pi}{180}$

One additional test is conducted to determine if the avoidance function should be ended. If the vehicle was maneuvering at the previous sample time, the maneuver is continued even if $\psi_{command} - \psi_{real} < TOL$ or $d = \infty$. This test prevents chattering.

The critical distance calculated in the preceding section cannot be used for threshold distance because in real situations, the thrust is used not only to slowdown the

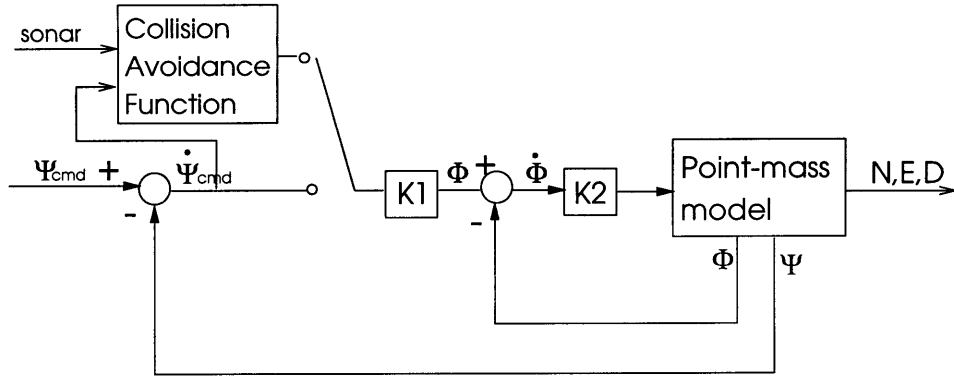


Figure 7-5: Simplified Block Diagram of Point-Mass Simulation

velocity component which makes the vehicle approaching the obstacle but also to change the flight direction for a detour, therefore, in addition to the critical distance, some margin should be added for the threshold distance.

A point mass simulation was done for the above algorithm by using Simulink. In the simulation, I chose 12° for TOL and $G = 1$ for the gain, therefore, a simple feedback system. Both of them must be chosen carefully because they determine how fast the vehicle goes back to the commanded heading; the tolerance determines the condition where the collision avoidance function has to stop and the gain effects on yaw rate at which the vehicle returns to the commanded heading.

7.3 Simulation

For simplicity, obstacles are made to be straight-edge walls in this simulation, and it is assumed first that the vehicle flies at an initial velocity of 5.5 m/s and just one obstacle is used for each simulation. Figure 7-6 shows how the vehicle behaves when it detects that there is an obstacle in front of it. In both cases, commanded heading angle is zero.

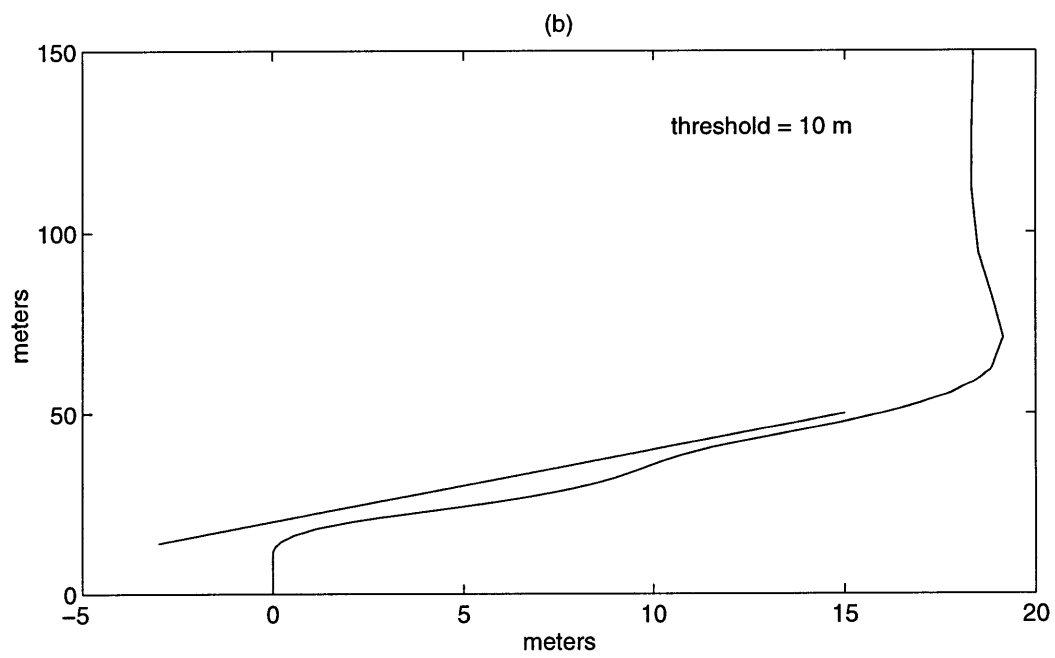
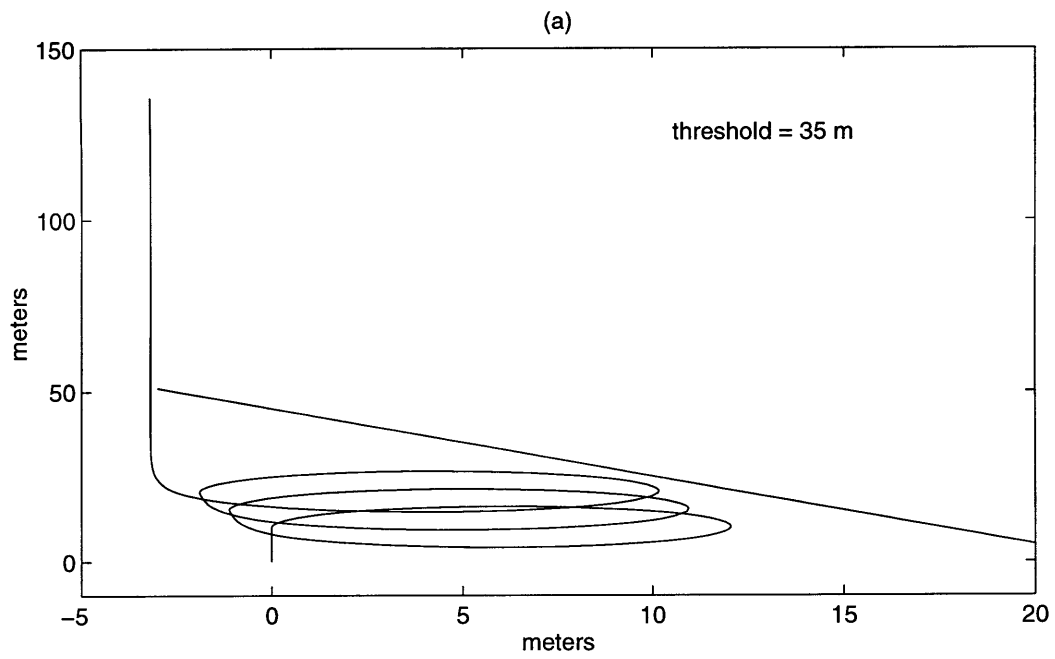


Figure 7-6: Flight Trajectories when $U_d = 5.5 \text{ m/s}$

Case (a): The algorithm in the preceding section makes the vehicle turn 360° when the obstacle lies like in this case. The vehicle keeps turning several times because the collision avoidance function does not turn off unless the heading error is small enough (in this simulation, 12°) and it detects no obstacle. Here, the turning radius of this vehicle is about 6 m , and the algorithm works only when the threshold distance guarantees sufficient space for the vehicle's turning. For this particular example, the threshold distance is 35 m , however, this may not be large enough. It has to be determined in such a way that between the vehicle and the obstacle, there should be enough room to make a 360° turn with turning radius of about 6 m . If the threshold distance is too small the vehicle will hit the obstacle inevitably (see Figure 7-7.)

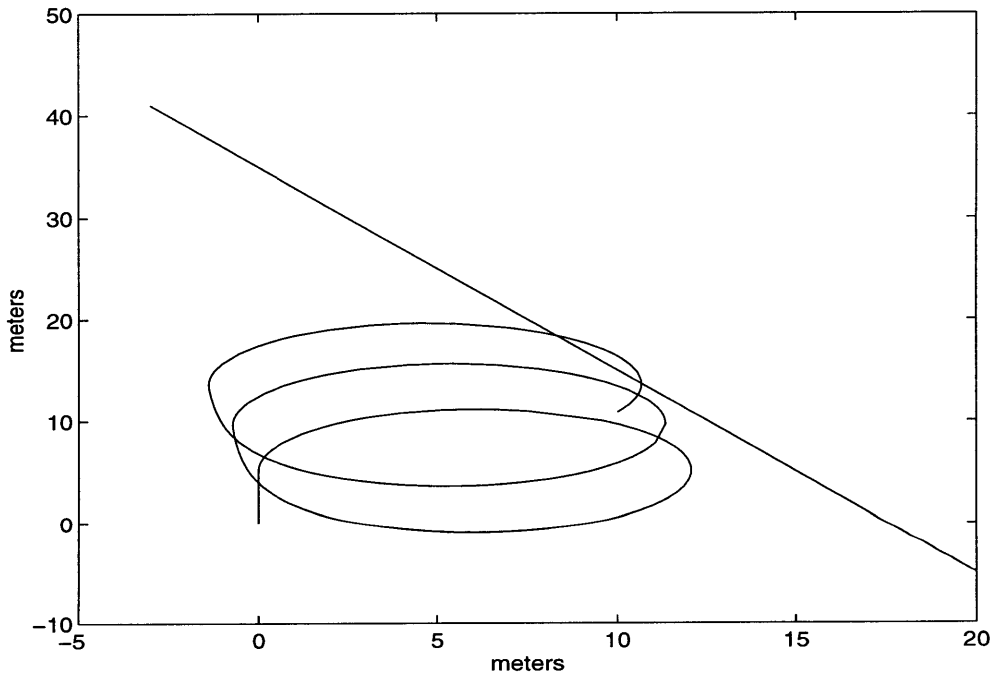


Figure 7-7: Flight Trajectory with Small d_{th}

Case (b): The vehicle successfully detours the obstacle. The threshold distance is set to be 10 m . The vehicle starts turning ten meters before the obstacle and flies without collision. Although the distance between the vehicle and the obstacle is getting smaller at the end, the gap is still three meters in this case.

The reason that the vehicle has to turn 360° in Case (a) is because we fixed the vehicle to turn clockwise, and that is because we do not have enough information to figure out which direction is a right direction to detour. If we knew turning counterclockwise is better at threshold location in Case (a), the trajectory would be exactly a mirror image of Case (b). However, this is possible only when there is another sonar sensor so that comparison between two sonar sensors yields appropriate information. It is crucial to use more sonar sensors to achieve a perfect collision avoidance function.

Another simulation at $U_d = 0.54 \text{ m/s}$ is included in Appendix A with Simulink block diagrams used for this simulation. This simulation result demonstrates how the algorithm is intended to perform the collision avoidance function. As the initial velocity is small, the turning radius is also small that Case (b) actually succeeded.

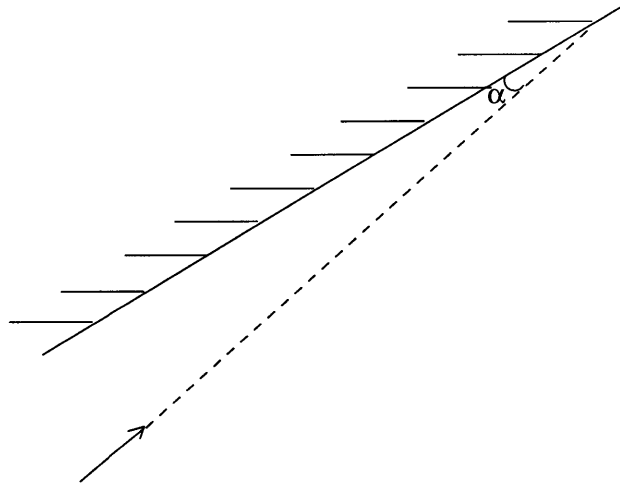


Figure 7-8: Approaching an Obstacle with Very Small Angle α

To achieve this algorithm successfully, the vehicle should approach the object with an appropriate angle α (see Figure 7-8.) When α is very small, even if the vehicle is close enough to make a collision, the sonar may not see the danger of collision because the sonar sensor will just detect the object still far away from the vehicle. Since the vehicle never knows how close the vehicle is flying relative to the object until the sonar detects $d \leq d_{cr}$ and makes a turn, this can be a critical issue in this algorithm.

The goal of the author was to develop a simple algorithm with using no memory. Shortcomings are because of one sensor, which may be overcome with more complex algorithm. For example, switching the turning direction after a complete turn may improve the algorithm. (See the unnecessary overturning in Case (a).) But this would add significant complexity and better not be pursued. Second sonar sensor is the best way to achieve a reliable collision avoidance system.

Chapter 8

Conclusions and Recommendations

As a stepping stone between existing UAV's and μ -UAVs, an S-UAV with state-of-the-art technology was feasibly designed and the design satisfied most of the customer requirements. Since accurate navigation systems and high quality payloads are costly, conflicts might occur in that most civilian customers want the S-UAV to have moderate functions at a reasonable price. For better and more practical S-UAV designs, further study is necessary. This design work may be a good starting point for further study in which the problems we came up with or we might have not noticed will be expected to be investigated and solved. The problems during this design process were:

Small vehicle control in winds and gusts. Since the S-UAV is very vulnerable to winds and gusts due to its size, maintaining its stability throughout an entire mission is one of the most subtle issues. As mentioned in D.R.Gordon's thesis [11], the vehicle should fly at a certain speed to overcome disturbances caused by wind and gusts. As the speed goes high, the vehicle becomes less susceptible to the disturbances. However, we cannot increase the speed as much as we want because there is another requirement that the vehicle should fly at a speed that it should not cause severe damages in case of collision. In civilian applications, where the damages are related to people, the flight speed has to be carefully chosen to satisfy both requirements.

Collision avoidance function. The collision avoidance issue with two sonar sensors is still pending. It is important for any application to which this design is focused. However, one sonar sensor is definitely not enough to make a perfect collision avoidance system. Although more sonar sensors may make the entire vehicle more expensive and heavier, they are essential to fly S-UAVs safely. The camera which is also attached at the front may be used as a supportive equipment to look for a possible dangerous objects ahead of the vehicle. But this may not be enough if the camera is already in use.

Appendix A

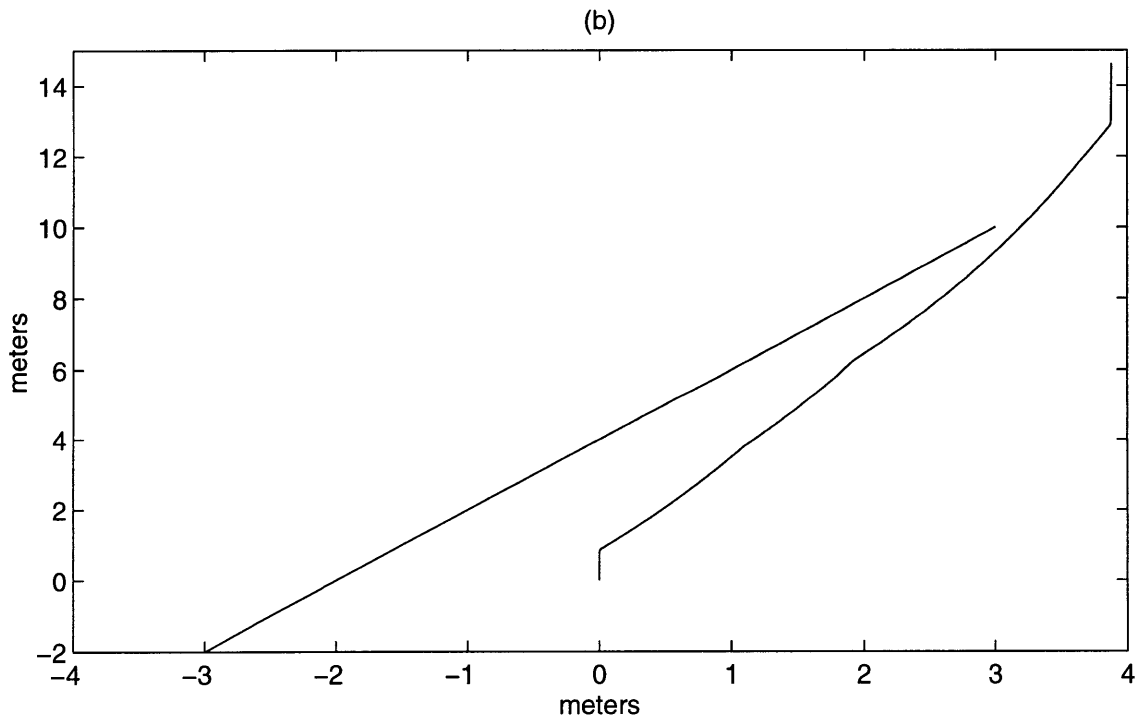
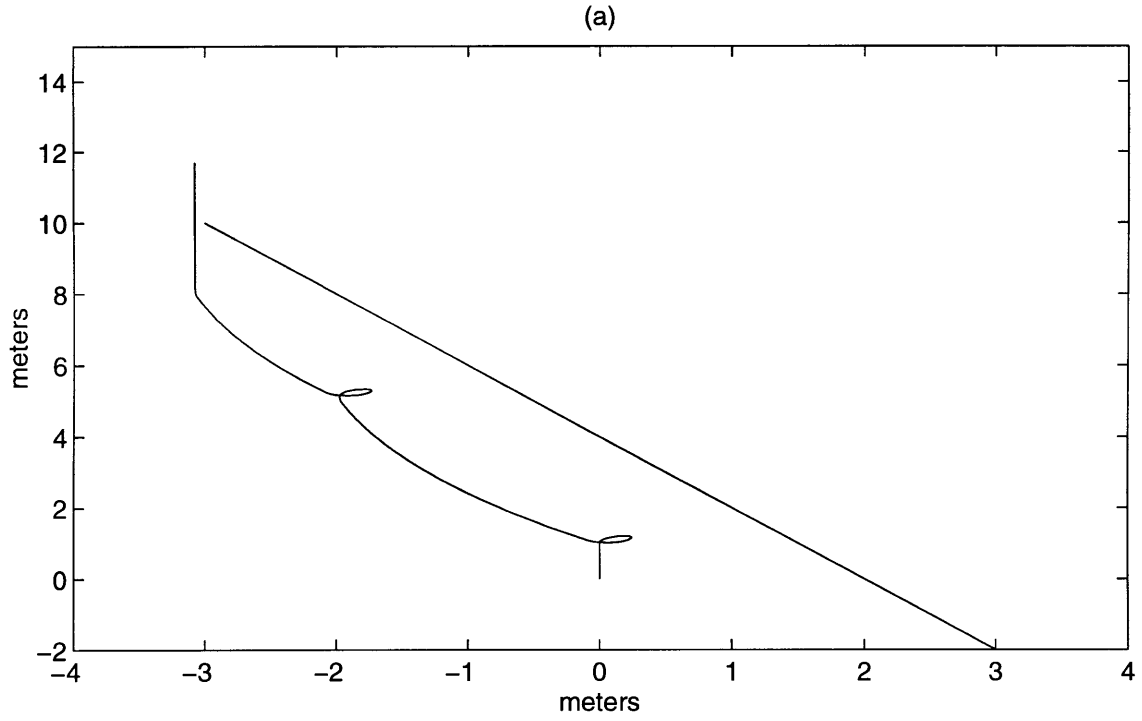


Figure A-1: Flight Trajectories when $d_{th} = 3.2 \text{ m}$, $U_d = 0.54 \text{ m/s}$ and $G = 0.01$

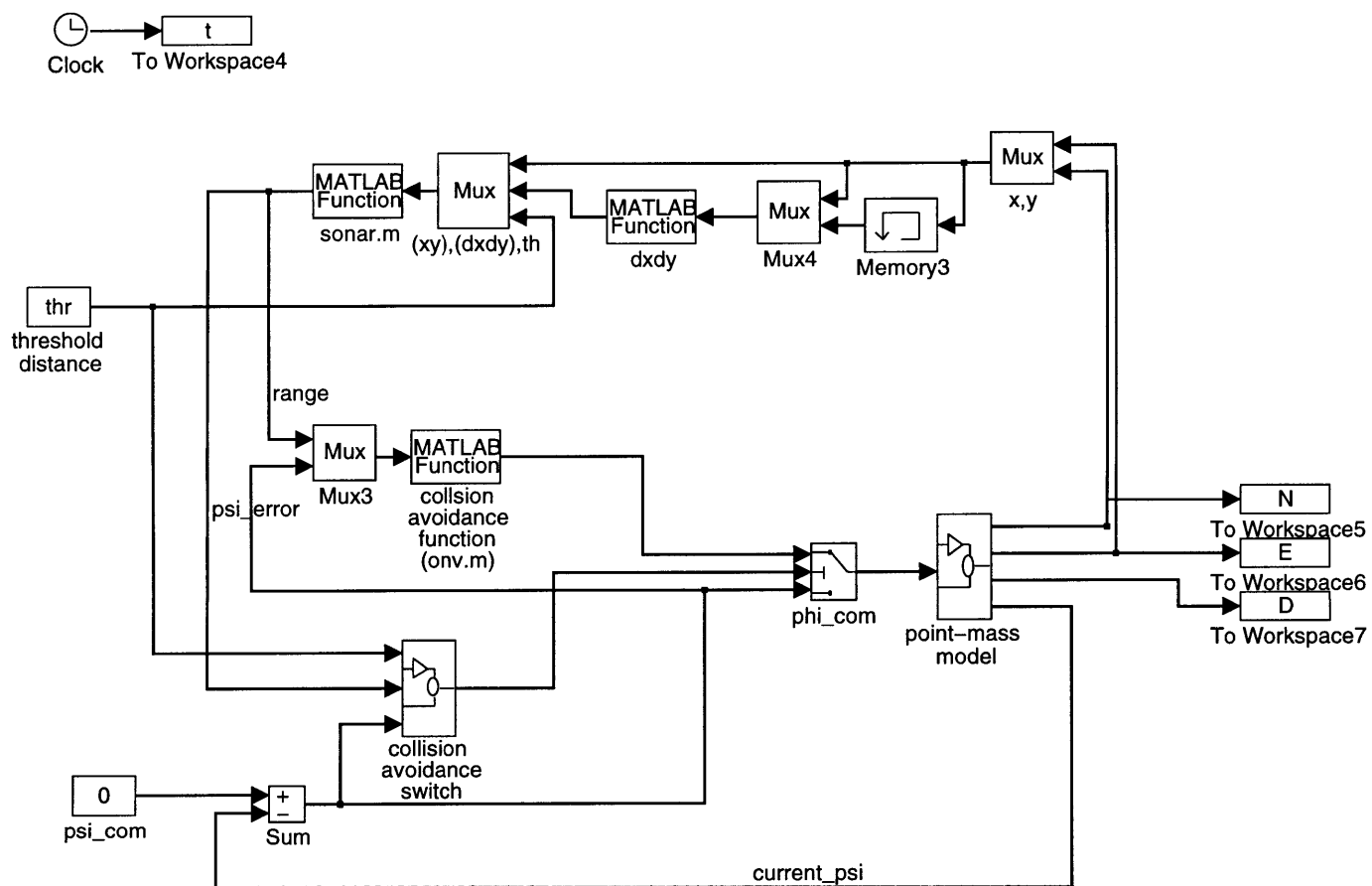


Figure A-2: Simulink Block Diagram of Collision Avoidance System

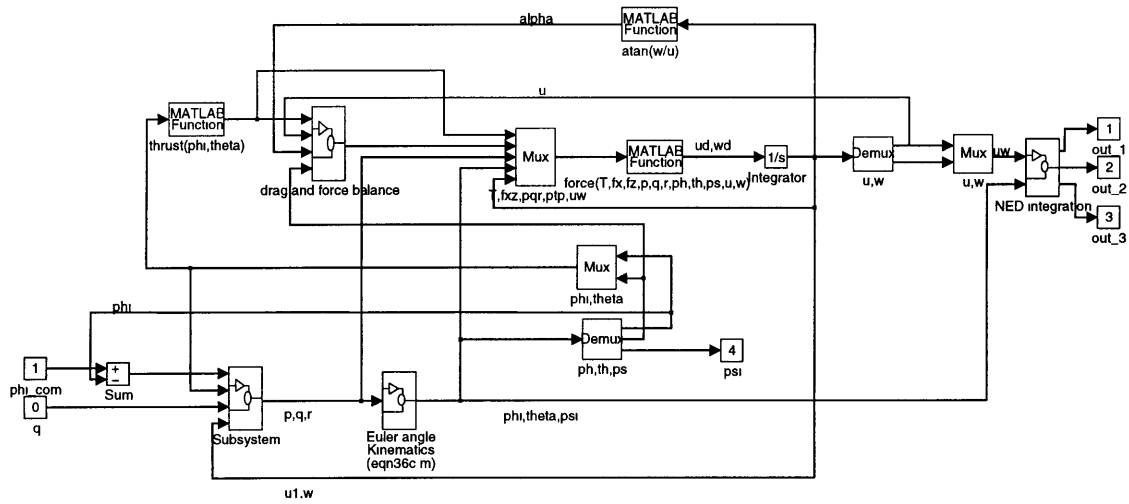


Figure A-3: Simulink Block Diagram of Point-Mass Model

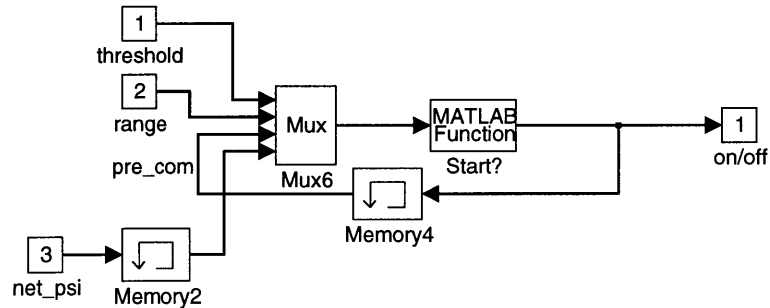


Figure A-4: Collision Avoidance Function Switch

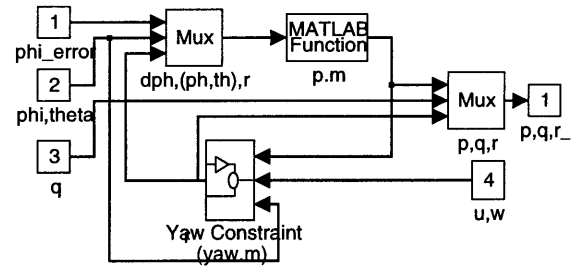


Figure A-5: Subsystem

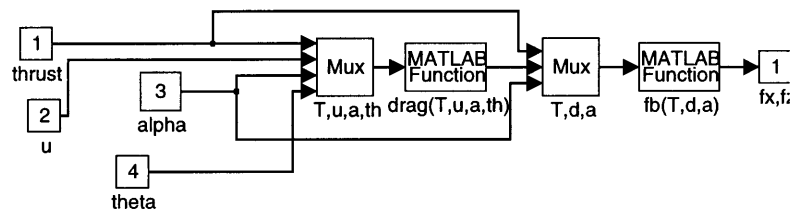


Figure A-6: Drag and Force Balance

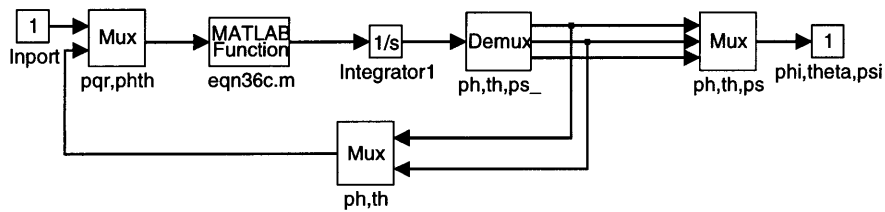


Figure A-7: Euler Angle Kinematics

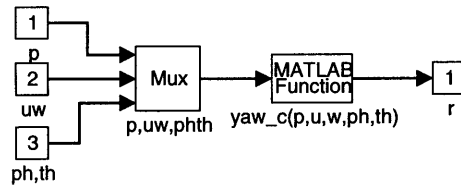


Figure A-8: Yaw Constraint

```
function Y = onv(d,psi_com)
```

```
%psi_com = net psi
```

```
out_of_range = 100;
```

```
phi_turn = 44*pi/180;
```

```
G = 1;
```

```
cpsi_com = rem(psi_com,2*pi);
```

10

```
if d == out_of_range
```

```
    phi_com = cpsi_com * G ;
```

```
else
```

```
    phi_com = phi_turn;
```

```
end;
```

```
function Y = strt(d,th,pre,npsi)
```

```
out_of_range = 100;
```

```
% This is a know output from sonar
```

```
% when wall is out of range
```

```
start = 1;
```

```
bhe = dar(npsi);
```

```

if d <= th
    Y = start;
elseif d == out_of_range & bhe < 12*pi/180
    Y = 0;
elseif pre == 0
    Y = start;
else
    Y = 0;
end;

```

```

function y = obsf1

```

```

% Obstacle function  $y = Ax + B$ 
%  $lo \leq x \leq up$ 

```

```

%A = 2;
%B = 20;
%lo = -3;
%up = 15;

```

```

A = -2;
B = 35;
lo = -3;
up = 23;

```

```

y = [A,B,lo,up];

```

```

function Y = sonar(x,y,dx,dy,th)

```

```

%slope =  $dy/dx$ ;

```

```

delta = atan2(dy,dx);

```

```

out_of_range = 100;

```

% Obstacle function 1

% $y = Ax + B$

10

res = obsf1;

A = res(1);

B = res(2);

lo = res(3);

up = res(4);

a = x + th*cos(delta);

b = y + th*sin(delta);

20

ox = (y-B-x*slope)/(A-slope); *% contact point on the wall*

oy = A*ox+B;

if ox > up | ox < lo

 d = out_of_range;

else

 d = sqrt((x-ox)^2+(y-oy)^2); *% sonar dectects range d*

end;

Y = d;

30

function y = thrust(phi, theta,d)

MASS = 1.4;

G = 9.81;

tem = abs(MASS*G/cos(theta)/cos(phi) + abs(d)/sin(theta));

if tem > 19.22

 y = 19.22;

else

 y = tem;

10

end;

function y = force(t, f_x, f_z, p, q, r, phi, theta, psi,u ,w)

v = 0;

G = 9.81;

MASS = 1.4;

udot = f_x/MASS + r*v - q*w - G*sin(theta);

wdot = f_z/MASS + q*u - p*v + G*cos(phi)*cos(theta);

y = [udot,wdot];

function y = p(dphi,phi,theta,r)

q = 0;

p = dphi - tan(theta)*(q*sin(phi)+r*cos(phi));

y = p;

function y = drag(T, u, alpha, theta)

rho = 1.225;

A = .0254;

V = (T/rho/A)^.5;

y = T*u/V;

function y =fb(t, d, alpha)

f_x = -d*cos(alpha);

f_z = -t - d*sin(alpha);

y = [f_x,f_z];

```
function y = eqn36c(p, q, r, phi, theta)
```

```
% Euler angle kinematics
```

```
% McRuer, Ashkenas & Graham
```

```
% Aircraft Dynamics & Automatic Control, pp223
```

```
phidot = p + tan(theta)*(q*sin(phi) + r*cos(phi));
```

```
thetadot = q*cos(phi) - r*sin(phi);
```

```
psidot = (q*sin(phi) + r*cos(phi))/cos(theta);
```

10

```
y = [phidot, thetadot, psidot] ;
```

```
function y = ned(u, w, phi, theta, psi)
```

```
v = 0;
```

```
Ndot = u*cos(theta)*cos(psi) + v*(-cos(phi)*sin(psi) + sin(phi)*sin(theta)*cos(psi))  
      + w*(sin(phi)*sin(psi) + cos(phi)*sin(theta)*cos(psi));
```

```
Edot = u*cos(theta)*sin(psi) + v*(cos(phi)*cos(psi) + sin(phi)*sin(theta)*sin(psi))  
      + w*(-sin(phi)*cos(psi) + cos(phi)*sin(theta)*sin(psi));
```

```
Ddot = -(u*sin(theta) - v*sin(phi)*cos(theta) - w*cos(phi)*cos(theta));
```

10

```
y = [Ndot, Edot, Ddot];
```

```
function r = yaw(p, u, w, phi, theta)
```

```
% Yaw constraint for a coordinated turn
```

```
G = 9.81;
```

```
r_temp = p*w + G*cos(theta)*sin(phi);
```

```
r = r_temp/u;
```

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